UNITED STATES

PATENT APPLICATION

Title: A SENSORY FEEDBACK SYSTEM FOR

ELECTROACTIVE POLYMER BASED

TRANSDUCERS

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A SENSORY FEEDBACK SYSTEM FOR ELECTROACTIVE POLYMER BASED TRANSDUCERS

FIELD OF INVENTION

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The present invention relates generally to an electroactive polymer based transducers and in particular electroactive polymer based transducers for use in inline sensory feedback and control system applications.

BACKGROUND OF THE INVENTION

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Position and force feedback are crucial requirements for high performance industrial and consumer based control applications. Such applications include micro and nano positioning, human interactive robotics, multi-agent robotics, toys, soft tissue handling and animatronics.

15 Traditional transducers include AC and DC motors, pneumatic, solenoid and hydraulic actuators. Sensory feedback from traditional transducers is commonly provided by additional components such as strain gages, accelerometers, laser interferometers, encoders, potentiometers, LVDTs, pressure sensors, load cells, and additional electroactive sensors. Each of these components requires extra power and

20 signal recovery circuitry. Furthermore, in space critical applications, the additional components commonly used to provide sensory feedback can interfere with the motion of the transducer and inhibit adequate operation of the device.

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Active mat rial based transducers are an alternative to the traditional transducers outlined above. Active material based transducers provide compact architectures for applications with limited space. In particular, electroactive polymers are active materials that commonly demonstrate high strain capability at lower

5   pressures than piezoceramic or magnetostrictive transducers. Therefore, such materials are especially suitable for large strain applications such as those listed above. In applications involving electroactive polymer transducers, the traditional approach to obtaining sensory feedback by addition of sensory components is cumbersome and with large strain transducers some methods of obtaining feedback

10   are seemingly impossible to implement. Furthermore, the addition of sensory elements to the transducer compromises the compact quality of electroactive polymer based devices that primarily attracts designers to these materials.

In view of the foregoing, an alternative, cost effective and compact electroactive polymer based transducer is desirable. Further, an electroactive polymer based

15   transducer for the inline sensing of strain, pressure, and health monitoring for electroactive polymer based transducers is also desirable.

SUMMARY OF THE INVENTION

The present invention relates to a system for obtaining inline sensory feedback

20   from an electroactive polymer based transducer for use in feedback control applications. The system infers strain, pressure and health of an electroactive polymer based transducer from real-time measurements of the electrical property changes.

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In one embodiment, during operation of the transducer, the inherent electrical properties of the electroactive polymer transducer are monitored with sensory signals to determine information regarding the state of the transducer. These measurements may be made with and without the presence of the potentially high voltage control

5   signal used to power the transducer. These measurements alone may be used to infer strain from the transducer in real-time position control applications.

In another embodiment, during operation of the transducer, both the high voltage signal applied to the transducer and the sensory signal may be measured and combined to infer both the strain state of the transducer and the electrostatic stress

10   applied to the transducer in real-time. These measurements are then useful as feedback for real-time impedance control applications.

In an additional embodiment, the combined measurement of the sensory signal and the control signal may be further manipulated with a microprocessor to determine the external disturbances that may be applied to the transducer. This information may

15   then be employed for real-time disturbance rejection or vibration suppression type control applications.

Furthermore, the sensory feedback system may be responsible for monitoring the health condition of the electroactive polymer transducer. In this case, in addition to the aforementioned measurements, the sensory system may monitor the power

20   delivery to the electroactive polymer transducer. These measurements may be used to prevent dielectric breakdown of the transducer or to cease power delivery to the transducer in the event of dielectric breakdown or mechanical failure of the device. In

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this case, the sensory feedback system acts as a watchdog to ensure safe operation of the transducer.

The system responsible for making the foregoing measurements from an electroactive polymer transducer is comprised of an amplifying stage, a sensory

5 feedback stage and a control stage. The amplifying stage includes a means by which to add the sensory signal to the control signal and provides power to the electroactive polymer transducer during operation. It also includes provision for an internal feedback control loop to improve the performance of the amplifying stage in supplying energy to the electroactive polymer transducer. The sensory feedback stage includes circuitry for

10 obtaining the feedback signals from the electroactive polymer transducer with and without the presence of the control signal. It also comprises signal conditioning circuitry, control/sensory signal separation circuitry, electrical property message extraction circuitry, and transient surge protection circuitry. The control stage comprises a computer, microcontroller or programmable logic circuit capable of

15 extracting the strain state information from the sensory feedback system with the assistance of a predetermined algorithm. Finally, the control stage also generates suitable control signals from the sensory signals obtained by the sensory stage with provision for user defined or pre-programmed commands.

20   BRIEF DESCRIPTION OF THE DRAWINGS

A more complete understanding of the invention and many of the achieved advantages thereof will b readily appreciated by reference to the following detailed

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description when considered in connection with the accompanying figures herein:

FIG. 1 is a block diagram of the sensory feedback and control system;

FIG. 2 is a block diagram of the amplifier and sensory tone generator;

FIG. 3 is a block diagram of the electroactive polymer transducer and sensory

5   circuitry; and

FIG. 4 is a block diagram of the sensory feedback circuitry.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

10   1. <u>General Structure of the Sensory Feedback and Control System for the</u>

<u>Electroactive Polymer based Transducer</u>

FIG. 1 is a block diagram for the sensory feedback and control system 100 for

measuring the electrical properties of the electroactive polymer transducer and sensory

circuitry 102. The user input 110 is integrated with the sensory feedback from the

15   sensory feedback circuitry 104 within the control system 106. A control signal 202 from

the control system 106 is delivered to the amplifier and sensory tone generator 108

where this signal is further combined with the internal feedback signal 204 from the

sensory feedback circuitry 104 and an internally generated sensory tone within the

amplifier and sensory tone generator 108 to produce the power signal 214. The power

20   signal 214 is then delivered to the electroactive polymer transducer and sensory

circuitry 102 in order to perform the task as dictated by the user input 110. During this

process, th surrounding environment acts upon the dielectric elastomer transducer in

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the form of an environmental disturbance 112. The environmental disturbance 112

may or may not be known prior to the operation of the electroactive transducer. Both

the power signal 214 from the amplifier and sensory tone generator 108 and the

environmental disturbance 112 determine the response of the electroactive polymer

5   transducer. This response in turn determines the changes in the electrical properties of

the electroactive polymer transducer and as such also determines the electrical output

from the electroactive polymer transducer and sensory circuitry 102. This sensory

signal is recovered by the sensory feedback circuitry 104 and is further filtered and

manipulated before returning to the control system 106 and the amplifier and sensory

10   tone generator 108. Finally, the control system 106 extracts information from the

sensory feedback signal and returns this information to the user as the data output 101.

The user input 110 may be provided from an external host computer or in the

form of input from an external supervisory program. The user input 110 may be a

position or force trajectory to be executed by the sensory feedback and control system

15   100 or it may be a command required to initiate completion of a pre-programmed

trajectory or to configure the data output 101 required from the sensory feedback and

control system 100.

The environmental disturbance 112 may represent a load applied directly to the

mechanical output of the electroactive polymer transducer. In this case, the

20   environmental disturbance 112 contributes to the strain state of the electroactive

polymer transducer. It is also possible to monitor an environmental disturbance 112

that acts upon the active region of the electroactive polymer transducer. In this case,

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the environmental disturbance 112 may damage or risk damage to the electroactive

polymer transducer and correspondingly decisions should be made within the control

system 106 to prevent further damage to the electroactive polymer transducer or the

surrounding environment. In this case, the sensory feedback circuitry 104 can detect

5   rapid changes in power delivery to the electroactive polymer transducer, which are

indicative of impending failure of the device under common operating conditions.

The data output 101 from the sensory feedback and control system 100 provides

the user with critical information regarding the performance of the electroactive polymer

transducer. This information may include real-time measurements of the electrical

10   properties of the electroactive polymer transducer, current, voltage or power

measurements from the amplifier and sensory tone generator 108, and health

monitoring data required to ensure safe operation of the transducer.

2. Electrical property changes for the electroactive polymer transducer

15   The global electrical properties of the electroactive polymer transducer change

during the operation of the device. The sensory feedback and control system extracts

this information from the transducer in real-time. An electroactive polymer transducer

consists of two or more electrodes sandwiching a single or multiple polymeric layers.

The electrical impedance of each electrode may change appreciably during operation

20   of the device. The impedance of the polymeric layers may also change appreciably

during the operation of the device. Furthermore, in some embodiments, both the

electrode and the polymeric lay r impedances change noticeably during operation. For

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a given device configuration, a correlation between the total strain of the transducer and the changes in the electrical properties of the electrodes, the polymeric layers, or a combination of the electrode and polymeric layers can be established.

Not wishing to be bound by any particular theory regarding the development of

5   the correlation between strain and electrical property changes, a simplified example is presented below. The following example is specific to planar dielectric elastomeric transducers operated in pure shear deformation. An example of such is found in a co-pending US application 10/644,894 filed August 21, 2003 and entitled Stretched Rolled Electroactive Polymer Transducer and Method of Producing Same, wherein a planar

10   transducer in pure shear is operationally equivalent to a ring type rolled transducer with a very thin electroactive polymer layer. The very thin electroactive polymer layer is generally less than 5% of the thickness of the entire roll. For a dielectric elastomer based polymeric layer, if the relative dielectric permittivity of the elastomer remains approximately constant during conformational changes, then the capacitance change

15   for the film can be related approximately to the axial strain and the initial capacitance of the polymeric layer by the following formula:

$$C = C_o \cdot (\varepsilon + 1)^2$$

20   Here c embodies the operational capacitance of the polymeric layer, c_o indicates the initial capacitance of the polymeric layer and ε represents the axial strain experienced by the polymeric layer during operation.

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In another example, a single ring rolled dielectric elasomer based transducer such as that described above in regard to the co-pending application is operated in pure shear deformation. In this example the rolled electroactive polymer transducer has a relatively thick active layer that is generally greater than 5% of the total diameter

5   of the roll. The correlation between the axial strain ε and the capacitance c of the polymer layer in a single ring rolled dielectric elastomer based transducer can be approximated as:

$$C = \frac{2C_o (\varepsilon + 1) \ln(\kappa)}{\ln\left[1 + \frac{\kappa^2 - 1}{\varepsilon + 1}\right]}$$

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where κ is the ratio between the inner and outer diameters of the rolled polymeric layer. In the case where the inner diameter of the layer approaches zero, the relationship approximately becomes:

15    $C = C_o (\varepsilon + 1)$

which is a linear relationship. In another case, where the thickness of the rolled electroactive polymeric layers are sufficiently thin, the relationship becomes approximately equal to that of the planar transducer:

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$C = C_o \cdot (\varepsilon + 1)^2$

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In the case that the inference of the applied electrostatic pressure is required from the electroactive polymer transducer, both the voltage and capacitance can be measured simultaneously. A correlation similar to the ones presented in the foregoing paragraphs

5   can be established for a given transducer morphology. As an example, the electrostatic pressure during operation of a planar dielectric elastomer based transducer under pure shear can be approximated by:

$$P_e = \frac{Cv^2}{h_0 A_0}$$

where P_e is the electrostatic pressure, c is the operational film capacitance, v is the

10   applied high voltage signal, h_0 is the initial polymeric layer thickness, and A_0 is the initial electroded surface area.

In these examples, the correlation between the strain state of the polymeric layer and the electrical capacitance of the layer is based on classical electrostatic theory. Many other means of determining the correlation between the electrical property

15   measurement and the strain state can be implemented such as by making independent *in situ* measurements for a particular device. These measurements are then used in establishing the required correlation by incorporating the independent measurements in conjunction with a lookup table, polynomial fit, neural network fit, fuzzy model fit or any other regression procedure.

20   As stipulated above, for a given device configuration, a correlation between the total strain of the transducer and the changes in the electrical properties of the electrodes, the polymeric layers, or a combination of the electrode and polymeric layers

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can b established. In the above examples, th correlation between the strain-state

and the electrical capacitance of the polymeric layer has been exemplified. For

electrodes, equivalent correlation to this presented herein for the polymeric layers can

be established based on the changes of the electrical properties of the electrodes

5   during conformational changes of the transducer. An example is presented below for a

wide group of carbon powder based electrodes (e.g., carbon conducting grease

(CW7100), conducting RTV silicone (RTV 60-CON), silver conducting grease

(CW7300), and graphite powder (S4)). The relationship between the strain and the

resistance of a carbon powder based electrode can be established experimentally or

10   approximated theoretically. From experiments, the relationship between strain and

resistance of a carbon powder based electrode under uniaxial extension is

approximated by the relationship:

$$R = R_o \left(\gamma \right)^{\varepsilon}$$

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where R is the present electrode resistance, R_o is the initial electrode resistance, ε is

the axial strain, and γ is a material and geometry dependent parameter measured by

the relationship:

20   $$\gamma = \frac{R_i}{R_o}$$

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where $\dot{R}_i$ is the electrod resistance measured at a strain equal to 100%. The values of γ for a common geometry and various electrode materials are $\gamma = 4$ for carbon conducting grease (CW7100), $\gamma = 6.5$ for conducting RTV silicone (RTV 60-CON), $\gamma = 6.8$ for silver conducting grease (CW7300), and $\gamma = 22$ for graphite powder (S4). The

5　relationship between resistance and strain can then be used either in conjunction with capacitance measurements or separately to distinguish the strain state of the electroactive polymer transducer during operation.

The decision as to which properties to measure depends on the specific configuration of any embodiment of the transducer. For example, grease based

10　electrodes tend to undergo irreversible flow during the operation of the transducer and as such, the measurement of the electrical properties of the electrodes would not be warranted in this case and instead, measurements of the polymeric layer capacitance should be made. In another embodiment, if conductive particle impregnated elastomeric electrode materials are used, the electrode resistance can be accurately

15　and reliably measured during real-time operation. In this case it is convenient to measure the electrode resistance instead of the polymeric layer capacitance during operation.

Once the correlation is established for a particular electroactive polymer transducer, measurements involving this correlation can be made with the sensory

20　feedback circuitry 104.

3. General Structure of th Control System

The control system 106 receives user input 110 and control feedback signals 420 from the sensory feedback circuitry 104 to generate a control signal 202, which is then sent to the amplifier and sensory tone generator 108, and data output 101. The signal 202 that is sent to the amplifier and sensory tone generator 108 is applied to the

5 electroactive polymer transducer. The data output 101 is used for feedback to the user, information storage, health monitoring information, etc.

In one embodiment, the internal structure of control system 106 also comprises a suitable control algorithm used in the feedback control loop. In this case, the control architecture operates in the closed-loop mode to improve the performance of the

10 electroactive polymer transducer. The improved performance relates to increasing the bandwidth, improving the positioning or force control accuracy, or improving the disturbance rejection of the transducer. The control algorithm is derived for the particular morphology of the transducer specific to a particular application. The algorithm may also be developed based on any of numerous control theories well

15 known to those skilled in the art. In one particular embodiment, a tuned PID control algorithm may be used to control the response of the electroactive polymer transducer. The resulting algorithm is implemented in a computer program, a microcontroller, analog circuitry or a programmable logic circuit within the control system 106 for the purposes of closed loop control of the electroactive polymer transducer.

20 In another embodiment, the control system 106 comprises a means for implementing the correlation between strain state and electrical property measurements from the electroactive polymer transducer. For example, the correlation

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between the strain and capacitance measurements indicated earlier may be implemented in real-time software operating on a host computer that, itself, embodies the control system 106. In another example, the correlation may be pre-programmed on a PIC microprocessor or equivalent. Furthermore, the correlation may be hard

5   wired in the form of functional analog electronics. For the example provided earlier, an analog square root circuit may be tuned to exhibit the required correlation between electrical property measurements from a strain state of the electroactive polymer transducer.

In yet another embodiment, the control system 106 comprises both a means of

10   implementing the correlation between the strain state and electrical property measurement from the electroactive polymer transducer and a suitable control algorithm for feedback control of the device. In this case the algorithm and correlation may be implemented together in a single microprocessor, computer program etc. or implemented individually within the same control system 106.

15   In a further embodiment, the control system 106 comprises both a means of implementing the relationship between the strain and the stress states and the corresponding measurements of the applied voltage and electrical properties of the electroactive polymer transducer. Furthermore, the embedded correlation may be combined with a control algorithm for impedance control of the transducer.

20   In yet another embodiment, the control system 106 comprises a means of inferring the strain and stress states from applied voltage and electrical measurements from the transducer. In addition the control system 106 comprises a means of inferring

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disturbances applied to the transducer during operation. The resulting algorithm may be used in conjunction with a control algorithm to perform disturbance rejection with the electroactive polymer transducer.

In another embodiment, the control system 106 includes a means of monitoring the health of the electroactive polymer transducer. In one example, the aforementioned control system includes circuitry suitable for monitoring the current delivery to the electroactive polymer transducer. If the current exceeds some predefined maximum, due to the initiation of a dielectric breakdown process in the transducer or due to damage to the transducer from an external source, an emergency process is triggered in the remainder of the control system 106. This process may shut down the amplifier, limit the voltage applied to the amplifier or recoil the transducer by modifying the control signal or it may communicate the problem to the user through the data output 101.

In yet another embodiment, the control system 106 passes the user input 110 directly through to the amplifier and sensory tone generator 108. In this case, the control system 106 is invisible to the forward loop of the sensory feedback and control system 100. This configuration is useful for applications where the user input 110 is a function generator and the sensory feedback and control system 100 is used to characterize the electroactive polymer transducer. The control system 106 may include provision for passing the sensory signals from the sensory feedback circuitry 104 through to the user via data output 101.

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4. General Structure of the Amplifier and Sensory Tone Generator

FIG. 2 outlines the general structure of the amplifier and sensory tone generator 108. The control signal 202, provided by the control system 106, is combined with the amplifier feedback 204 from the sensory feedback circuitry 104 in the preamplification

5   stage 206. The preamplification stage 206 further acts as a buffer for the control signal 202 and the amplifier feedback 204 and passes the complete signal on to the amplifier 212. The amplifier 212 combines the signal from the preamplification stage 206 with the signal created by the sensory tone generator 208 into the completed power signal 214 that is delivered to the electroactive polymer transducer and sensory circuitry 102.

10   The protection circuitry 210 provides over-voltage protection to the sensory tone generator 208 in the event of a transient power surge through the system due to the accidental dielectric breakdown of the electroactive polymer transducer during operation.

The preamplification stage 206 combines the control signal 202 and the amplifier

15   feedback 204 to generate the low voltage signal that will be amplified to drive the electroactive polymer transducer. The preamplification stage 206 also acts as a pow r buffer for both the control signal 202 and the amplifier feedback 204. This stage comprises circuitry suitable for the combination of the control and feedback signals and further provides the control algorithm for the internal feedback loop. The internal

20   feedback control algorithm may be of any general form. In one example, the control algorithm simply provides proportional feedback control of the voltage applied to the

electroactive polymer transducer. This feedback improves the bandwidth capability of the amplifier 212 at the expense of the range of the output voltage.

In another embodiment, the preamplification stage comprises circuitry suitable for the combination of the control signal 202 and the amplifier feedback 204 with
5   provision for a control algorithm and voltage limiting circuitry. The voltage limiting circuitry provides a means of protecting the electroactive polymer transducer from accidental over-voltages created by the amplifer 212.

The sensory tone generator 208 creates the sensory tone that is used to extract the electrical property data from the electroactive polymer transducer. The sensory
10   tone is a low voltage signal with amplitude between 1mV and 10V. The sensory tone may be created anywhere between 1Hz to 1MHz with the optimal frequency for the tone being determined by the specifics of an application. These specifics are defined by both the detailed design of an electroactive polymer transducer (e.g., its polymeric material and design arrangements) and the intended use (e.g., desired precision of
15   positioning and force control, desired sensing specifications for strain, pressure, and health monitoring). The sensory tone generator 208 can be comprised of function generating, pseudo-sine wave generating, or sine wave generating circuitry.

In the case that the sensory tone generator 208 comprises a function generator, the function generator may be any general function generator. For example, the
20   function generator may be a BK Precision 4011A 5MHz function generator or equivalent. In applications requiring high precision, an Agilent 33120A 15MHz Function/Arbitrary waveform generator may b   used as the function generator.

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In the case that the sensory tone generator 208 comprises pseudo-sine wave generating circuitry, the circuitry may be of the wave shaping type or may be an oscillator such as a Wien bridge sine wave oscillator. Filtering the harmonic content from a square wave signal may also create an appropriate sensory tone. Furthermore,

5   a single chip such as the XP 2205CP Sine Wave Generator, the ML2035 Serial Input Programmable Sine Wave Generator from Fairchild Semiconductor, or the AD2S99 Oscillator from Analog Devices among others may embody the circuitry of the sensory tone generator 208. In the case that the sensory tone is created using a low power oscillator, the output from the oscillator may have to pass through a power amplifier

10   before being delivered to the amplifier 212.

The amplifier 212 creates a sufficiently high voltage power signal in sync with the input signals to drive the electroactive polymer transducer. The output from the amplifier 212 should be tailored to specific application at hand. The output voltage requirements commonly range between 0-20kV while the power requirements for

15   driving electroactive polymer transducers commonly range from 10mW to 10kW. The exact voltage and power demand for any application is dependant on the dimensions of the electroactive polymer transducer, the capacitance of the transducer, and the bandwidth requirements for the application. In applications with low power demands, a low power DC-DC converter may embody the amplifier 212. An example of such a

20   converter is the DX200 DC-DC converter available from EMCO High Voltage. This converter outputs a signal between 0-20kV given an input ranging between 0-12V.

The signal created by the sensory tone generator 208 is combined with the output from the preamplification stage 206 at the amplifier 212. The signals may be combined at the input to the amplifier 212 or at the output from the amplifier 212.

The signals are combined at the input to the amplifier 212 in cases where the amplifier 212 requires an earth ground reference for the output signal or where the power demands are such that the safe combination of signals at the output from the amplifier 212 is not possible. The DX200 DC-DC converter should have an earth grounded reference for the output signal. As such, the sensory signal cannot be easily added to the output signal without extra circuitry. Therefore, the sensory signal should be added to the output from the preamplification stage 206 at the input to the amplifier 212. In this case, the sensory signal should be much smaller than the output from the preamplification stage 206.

In one embodiment, the sensory tone is added to the output of the preamplification stage 206 at the input to the amplifier 212. The sensory tone has an amplitude between 1-10mV while the preamplification stage 206 output has an amplitude between 0 – 12V. For this type of implementation, the sensory signal should be as consistent as possible to ensure that the power signal 214 generated by the amplifier 212 contains an easily recoverable sensory tone. In the case where the signals are added at the input to the amplifier 212, the protection circuitry 210 is not essential for the protection of the sensory tone generator 208.

The signals are combined at the output from the amplifier 212 in cases where the amplifier 212 has significant isolation between the input and output stages and

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where the power demands from the amplifier 212 are low enough that the safety during

accidental dielectric breakdown of the electroactive polymer transducer can be

minimized. The Q101-5 DC-DC converter available from EMCO High Voltage is

capable of this type of operation. This DC-DC converter can maintain output isolation

5   of up to 500V from the ground referenced input signal.

In this case, the sensory tone generator 208 can be connected directly to the

reference of the power signal 214 from the amplifier 212. The sensory tone is much

larger in this case as compared to the case where it is added at the input to the

amplifier 212. If added to the output from the amplifier 212, the sensory tone has an

10   amplitude between 500mV – 20V. The amplitude of the sensory tone is small in

comparison to the high voltage output from the amplifier 212. As such, the sensory

tone does not contribute significantly to the transduction of the electroactive polymer

transducer. In the case that the sensory tone is added to the output of the amplifier

212, the consistency of the sensory tone does not have to be as accurate as when it is

15   added to the input to the amplifier 212. Although, in this case, the sensory tone

generator 208 should be protected from transient surges that may occur due to the

accidental dielectric breakdown of the electroactive polymer transducer.

The protection circuitry 210 provides a means of protecting the sensory tone

generator 208 from transient surges that may propagate through the system in the

20   event that the electroactive polymer transducer should fail during operation. The

protection circuitry 210 may be embodied by a series of nonlinear resistors, varistors or

zener diodes or a combination of such circuit elements. In one embodiment, the

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protection circuitry 210 compris s the parallel combination of a pair of 1N4743A zener

diodes and an ERZ-V05D180 Transient/Surge Absorber available from Panasonic.

The zener diodes offer a first defence against a transient power surge and the

Transient/Surge Absorber provides the second defence in case the zener diodes fail

5   due to the power surge.   The Transient/Surge Absorber comprises a capacitive

component and a nonlinear resistive component that together provide a very large load

for transient surges but present a relatively small load for the sensory tone generator

208. The protection circuitry 210 may be significantly more complex than the example

provided here or may simply comprise a pair of zener diodes.

10   In the case that the amplifier 212 is comprised of a DC-DC converter or a

voltage amplifier of similar structural makeup, the amplifier 212 automatically generates

a high frequency tone that is superimposed on the power signal 214. This tone is

usually a by-product of the circuitry used in these devices to create the high voltage

signal. In one example, a Q101-5 DC-DC converter creates a triangular low voltage

15   signal, less than 100V in amplitude, with a fundamental frequency of a low voltage of

approximately 60kHz. In cases where the electrical properties of the electroactive

polymer transducer favour the application of a sensory tone in the range of 50 – 75kHz

or more, the low voltage output from the amplifier 212 may embody the sensory signal

and the extra sensory tone generator 208 is not required. Furthermore, some DC-DC

20   converters produce a high frequency, low voltage tone that is closer to a pseudo sine

wave than the Q101-5. Such DC-DC converters, such as the DX200 are preferred over

the Q101-5 in applications where th   amplifier 212 internally generates the sensory

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tone. Ideally, the existing DC-DC converters would be modified to supply an accurate sine wave sensory tone at a tuneable frequency without the need for any extra circuitry.

5. <u>General Structure of the Elastomer Transducer and Sensory Circuitry</u>

5   FIG. 3 is a block diagram of the electroactive polymer transducer and sensory circuitry 102 and the connections between this system and the surroundings. The power signal 214, provided by the amplifier and sensory tone generator 108, is applied to both the electroactive polymer transducer 306 and the sensory circuitry 308. The electroactive polymer transducer 306 responds to the combined influence of the power

10   signal 214 and the environmental disturbance 112. The electroactive polymer transducer 306 responds to these influences by changing shape. This shape change causes the aforementioned variation in the electrical properties of the electroactive polymer transducer 306. The amplitude of the sensory signal 312, from the sensory circuitry 308, changes in response to the electrical property variation of the

15   electroactive polymer transducer 306. The total signal 314 is recovered from the combination of the electroactive polymer transducer 306 and the sensory circuitry 308 in the case that the power signal 214 is required for feedback control or that the power signal 214 is not strong enough to ensure that the amplitude content of the sensory signal is maintained during normal operation of the electroactive polymer transducer

20   306. The protection circuitry 310 provides transient surge protection to the sensory circuitry 308 in the event of accidental dielectric breakdown of the electroactive polymer transducer 306 during operation.

The electroactive polymer transducer **306** is comprised of at least one polymeric

layer encapsulated between two or more compliant electrodes. The electroactive

polymer transducer **306** is interfaced to the surrounding environment via mechanical

attachments. The surrounding environment interacts with the electroactive polymer

5   transducer **306** by means of an external disturbance **112**. This disturbance may be the

load that is driven by the electroactive polymer transducer **306**, or it may also comprise

an unexpected disturbance.

The sensory circuitry **308** is used to create the sensory signal that monitors the

electrical property changes of the electroactive polymer transducer **306**. The sensory

10   circuitry **308** is designed as the first stage for the extraction of the sensory signal **312**.

As such, the proper design of the sensory circuitry **308** is crucial for the effective

operation of the sensory feedback and control system.

In one embodiment, the sensory signal **312** is selected for a frequency spectrum

in excess of that reserved for the control signal content. In this case, the sensory

15   circuitry **308** is designed such that the power delivery to the electroactive polymer

transducer **306** is not inhibited within the bandwidth prescribed for the control content of

the power signal **214**. The other requirement imposed on the design of the sensory

circuitry **308** is that it creates a sufficiently wide pass band within the frequency

spectrum designated for the placement of the sensory tone. Furthermore, it is

20   important to define a correlation between the changes in the sensory signal **312** to the

electrical property changes of the electroactive polymer transducer **306** within the pass

band frequency spectrum. The other requirement imposed on the design of the sensory

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circuitry **308** is that it also prevents amplification of high frequency nois   due to

switching circuitry and during accidental transient surges. The electrical properties of

the protection circuitry **310** should also be examined during the design of the sensory

circuitry **308**. There are many embodiments of the sensory circuitry **308** that can be

5   tailored to achieve the aforementioned requirements. In one embodiment, the sensory

circuitry **308** comprises the parallel connection of a capacitor and a resistor.

The capacitor and the resistor are selected for a particular electroactive polymer

transducer **306** based on the electrical properties of the transducer without the applied

power signal. In one case, the electrical properties of the electroactive polymer

10   transducer **306** without applied voltage can be approximated as a series connection of

a resistor and a capacitor. Particular to the example presented here, the capacitance

of the electroactive polymer transducer **306** is $C_o = 132\,pF$ and $R_o = 10.5\,k\Omega$. The electrical

properties of the electroactive polymer transducer **306** change under the applied

voltage as approximated by the correlations presented earlier. Assuming that the

15   control signal spectrum is sufficiently lower than that reserved for the sensory tone, the

design of the sensory circuitry **308** can be approached using small signal analysis of

the electrical circuitry comprising the electroactive polymer transducer **306** and the

sensory circuitry **308**.

Using small signal analysis, the transfer function relating the power signal **214** to

20   the sensory signal **312** is defined for the simple example of a parallel connection of a

capacitor and resistor by:

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$$\frac{v_o(s,\varepsilon)}{v_{in}(s,\varepsilon)} = \frac{R_s C(\varepsilon)s}{R_s R(\varepsilon)C_s C(\varepsilon)s^2 + \{R_s(C_s + C(\varepsilon)) + R(\varepsilon)C(\varepsilon)\}s + 1}$$

where v_o is the sensory content of the power signal 214 applied to both the

electroactive polymer transducer 306 and the sensory circuitry 308 and v_{in} is the

5   sensory signal 312. The sensory circuitry electrical parameters for the resistor and

capacitor are designated by R_s and C_s respectively. To satisfy the predetermined

requirements for the sensory circuitry 308 demonstrated by this example, the properties

of the sensory circuit should be selected according to:

10    $$w_s = \frac{1}{R_s C_s} \ll w_{DET} = \frac{1}{R(\varepsilon)C(\varepsilon)}$$

$$C_s \gg C(\varepsilon)$$

$$R_s \approx R(\varepsilon)$$

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After these conditions are determined for the parameters of the sensory circuitry 308,

the sensory signal 312 can be related to the total signal 314 by the approximate

relationship:

20    $$\frac{V_o(s)}{V_{in}(s,\varepsilon)} \approx \frac{C(\varepsilon)}{C(\varepsilon) + C_s}$$

and in the case where the sensory capacitor designated c, is much larger than the capacitance of the electroactive polymer transducer **306** then the above relationship can be further reduced to:

5
$$\frac{V_o(s)}{V_{in}(s,\varepsilon)} \approx \frac{C(\varepsilon)}{C_s}$$

and a linear relationship can be established between the capacitance change in the electroactive polymer transducer **306** and the change in amplitude of the sensory signal **312**.

10   In another embodiment, the resistance change of the electrodes for the electroactive polymer transducer **306** can be monitored using similar concepts with differently selected sensory circuitry **308**. A design methodology similar to that presented herein would be clear to those skilled in the art.

In yet another embodiment, both the resistance change of the electrodes and

15   the capacitance change of the polymeric layer can be measured in combination from the electroactive polymer transducer **306** to infer its strain state. A design methodology similar to that presented herein would be clear to those skilled in the art.

The protection circuitry **310** provides a means of protecting the sensory circuitry **308** from transient surges that may propagate through the system in the event that the

20   electroactive polymer transducer **306** should fail during operation. The protection circuitry **310** may be embodied by a series of nonlinear resistors, varistors or zener diodes or similar protective circuit elements. In one embodiment, the protection

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circuitry **310** comprises the parallel combination of a pair of 1N4743A zener diodes and an ERZ-V05D180 Transient/Surge Absorber available from Panasonic. The zener diodes offer a first defence against a transient power surge and the Transient/Surge Absorber provides the second defence in case the zener diodes fail due to the power

5   surge. The Transient/Surge Absorber comprises a capacitive component and a nonlinear resistive component that together provides a very large load for transient surges. The electrical properties of these components should be considered in the design of the sensory circuitry **308** as they can have an effect on the overall properties of the transfer function for the sensory signal **312**. The protection circuitry **310** may be

10   significantly more complex than the example provided here or may simply comprise a pair of zener diodes.

6. General Structure of the Sensory Feedback Circuitry

FIG. **4** is a block diagram of the sensory feedback circuitry **104**. The total signal

15   **314** is measured from the electroactive polymer transducer and sensory circuitry. The amplitude of the total signal **314** is safely divided to a predetermined scale by the voltage reduction circuitry **406**. The reduced total signal **316** is then sent to the control signal preamplification stage **408** and the sensory signals preamplification stage **412** for signal conditioning. The sensory signal **312** is measured from the sensory circuitry

20   and delivered immediately to the sensory signals preamplification stage **412**. The control signal preamplification stage **408** buffers and amplifies the reduced total signal **316** generated by th   voltage reduction circuitry **406**. The amplified total signal **318**

from the control signal preamplification stage 408 is then sent to the control signal

extraction filters 410 where the control signal content is extracted from the amplified

total signal 318 generated by the control signal preamplification stage 408. The

recovered and conditioned control signal generated by the control signal extraction

5   filters 410 is then sent to the rectification and sampling stage 416 where it is routed

either to the control system 106 via the control system feedback 420 or to the amplifier

and sensory tone generator 108 via the amplifier feedback 204. The sensory signal

312 is amplified and buffered in the sensory signals preamplification stage 412 and

then sent through to the sensory signals extraction filters 414 where any remnants of

10   the control signal or high frequency noise are removed from the sensory signal. The

amplified and filtered sensory signal 402 generated by the sensory signals extraction

filters 414 is then sent to the rectification and sampling stage 416 where the electrical

property measurements from the electroactive polymer transducer are extracted from

the sensory signal 402. Finally, the extracted signal content is routed to the control

15   system 106 or the amplifier and sensory tone generator 108 via the control system

feedback 420 or the amplifier feedback 204, respectively.

The voltage reduction circuitry 406 reduces the potentially high voltages

associated with the total signal 314 to amplitudes that are safe for the remaining low

voltage circuitry. Common operating voltages for the total signal 314 range from 0 to

20   20kV and the voltage reduction circuitry 406 reduces the amplitude of this signal to

within the common range of 0 to 20V. The reduced total signal 316 generated by

voltage reduction circuitry 406 can then be safely monitored and manipulated by the

remaining low voltage circuitry. There are several embodiments of the voltage

reduction circuitry 406 that may satisfy the criteria outlined above. Someone familiar

with the art could implement several various embodiments for the voltage reduction

circuitry 406. In a particular embodiment, the voltage reduction circuitry 406 is

5   comprised of a 1000:1 voltage divider model V1G available from EMCO High Voltage.

The reduced total signal 316 generated by voltage reduction circuitry 406 is sent

to the control signal amplification stage 408. This stage is responsible for buffering the

reduced total signal 316 and preamplifying this signal in preparation for the control

signal extraction filters 410. In many cases the buffering amplifiers within the control

10   signal preamplification stage 408 will contain an active shield to protect the sensitive

output of the voltage reduction circuitry 406 from stray capacitance and board

resistance. It is understood that this form of buffering may be performed by many

varieties of circuitry familiar to someone skilled in the art. In one instance the reduced

total signal 316 is buffered and shielded by one channel of the quad operational

15   amplifier TL084 available from STMicroelectronics. Furthermore, the amplification

stages within the control signal amplification stage 408 modify the buffered signal to

optimize the amplitude of the signal for the control signal extraction filters 410.

After being buffered and amplified, the reduced and amplified total signal 318

generated by the control signal preamplification stage 408 is sent to the control signal

20   extraction filters 410. The control signal extraction filters 410 remove the residual

sensory tone and high frequency noise from the reduced and amplified total signal 318

leaving only the control signal for feedback to the control system. The control signal

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extraction filters 410 comprise a series of low pass filters to adequately remove the high frequency content from the reduced and amplified total signal 318 leaving only the portion of the signal responsible for the control of the electroactive polymer transducer. The filters may be designed using a variety of components including digital signal

5   processors, analog filters, active filters, and digital filters among others. In one embodiment the control signal extraction filters 410 comprise a series of 2nd order switched capacitor filtering stages. The filters are implemented on LMF100 switched capacitor filters available from National Semiconductor. The circuitry is configured as staged 2nd order notch-low pass filter and high-Q low pass filters to remove the sensory

10   signal 312 content from the total signal 314 and remove all high frequency noise from the signal. This leaves only the control signal content at the output of the control signal extraction filters 410. This signal is sent onto the rectification and sampling stage 416 for rerouting.

The sensory signal 312 is delivered directly to the sensory signals

15   preamplification stage 412. The sensory signal preamplification stage 412 includes provision to accept sensory signal content from both the sensory signal 312 and the reduced total signal 316. This is required in the case where the amplifier cannot consistently supply the sensory tone to the electroactive polymer transducer or in cases where a transient surge is propagated through the system due to dielectric breakdown

20   of the electroactive polymer transducer. In cases where these events are not likely to occur, the sensory signals preamplification stage 412 may only accept the sensory signal 312. In either case, the signals are amplified in this stage of the circuitry. The

amplification acts both as a buffer and to modify the input voltages to an acceptable range for the sensory signals extraction filters 414. This circuitry stage is similar in nature to the control signal preamplification stage 408. In this sense, the circuitry used in each stage can be common to both. In one embodiment, sensory signal 312 is

5   buffered and amplified by multiple channels of a quad operational amplifier TL084 available from STMicroelectronics. After preamplification stage 412, the sensory signal 312 and the reduced total signal 316 are delivered to the sensory signals extraction filters 414.

The sensory signals extraction filters 414 remove the control signal content and

10   noise residuals from the sensory signal 312 and potentially from the total reduced signal 316. The sensory signals extraction filters 414 comprise a series of band pass filters to adequately remove the high frequency content from the amplified sensory signal 312 and the total reduced and amplified signal leaving only the portion of the signal responsible for the sensory feedback from the electroactive polymer transducer.

15   The filters may be designed using a variety of components including digital signal processors, analog filters, active filters, and digital filters among others. In one embodiment the sensory signals extraction filters 414 comprise a series of 2nd order switched capacitor filtering stages. The filters are implemented on LMF100 switched capacitor filters available from National Semiconductor. The circuitry is configured as

20   staged 2nd order band pass filters to remove the control signal content from the amplified sensory signal 312 and the total reduced and amplified signal and remove all high frequency noise from the signals. This leaves only the sensory signal content at

the output of the sensory signals extraction filters 414. Th signals 402 are sent onto the rectification and sampling stage 416 for further modification and rerouting.

The rectification and sampling stage 416 extracts the electrical measurement content from the feedback signals from the electroactive polymer transducer. In one
5   embodiment, the sensory tone is a high frequency tone used to extract the electrical information from the electroactive polymer transducer. In this case, the rectification and sampling stage 416 removes the high frequency sensory tone from the sensory signals and leaves the electrical measurement signal. The sensory tone is the carrier and the electrical measurements represent the message, encoded as the amplitude
10   modulation of the sensory tone. To remove the electrical measurements from the sensory tone, a wide variety of demodulation schemes may be employing. In particular, in one embodiment, a synchronous demodulation scheme is used to extract the electrical measurements from the sensory signals. To enhance the frequency response of the output signal, the signal is rectified and sampled. The rectification of
15   the sensory signal can be achieved using many different methods familiar to one skilled in the art. In one embodiment the signal is rectified using an active rectification circuit. After rectification, the envelope is representative of the electrical measurements and should be extracted from the completed signal. This task can be performed by a number of envelope detection schemes. For example, the envelope can be detected
20   using a passive envelope detection scheme. In another embodiment, the envelope detection scheme is done by synchronously resampling the rectified signal at successive peaks in the carrier. This task is performed using multiple LM339

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comparators, a LMC555 timing circuit and a LF398 sample and hold circuit available from National Semiconductor. This procedure significantly reduces the phase lag between the detected envelope and the actual envelope over passive envelope detection schemes.

5   The rectified signal is filtered using a variety of passive or active filters to remove any high frequency noise introduced by the sensory signals extraction filters 414 and the rectification and sampling stage 416.

After extraction of the electrical measurement content, the signals are rerouted to the amplifier and sensory tone generator in the form of the amplifier feedback 204

10   and to the control system in the form of the control system feedback 420, thereby completing the control loop and delivering sensory information from the electrical property changes of the electroactive polymer transducer to the control system 106 and the amplifier and sensory tone generator 108.

As used herein, the terms "comprises" and "comprising" are to be construed as

15   being inclusive and opened rather than exclusive. Specifically, when used in this specification including the claims, the terms "comprises" and "comprising" and variations thereof mean that the specified features, steps or components are included. The terms are not to be interpreted to exclude the presence of other features, steps or components.

20   It will be appreciated that the above description related to the invention by way of example only. Many variations on the invention will be obvious to those skilled in the art and such obvious variations are within the scope of the invention as described

herein whether or not expressly described. Further, other embodiments and

modifications of the present invention may be possible in light of the foregoing

exposition. Therefore, it is to be understood that the present invention is not to be

limited to the exposition presented and that such further embodiments and

5   modifications are intended to be included in the scope of the appended claims.